LTCC or LCP, A COMPARISON USING CAVITY BACKED SLOT ANTENNAS with PIN CURTAINS at 60 GHz

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***Abstract*—LTCC and LCP technologies are compared at 60 GHz antenna design in terms of antenna polarization purity and efficiency. Cavity backed slot (CBS) antennas with pin curtain walls are chosen as the antenna element and modelled using FDTD technique. The performances of the antennas are analysed while changing the substrate used. Substrate losses and conductor losses are calculated and total radiated powers in lossy and lossless cases are studied to reach the final efficiency figures. CBS antenna on LCP is found to be more efficient and have better radiation properties.**

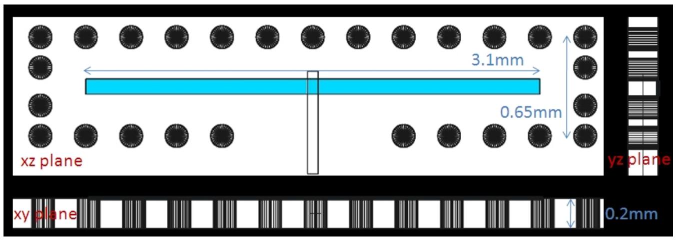
I. Introduction

Millimeter wave systems are drawing more and more attention as the process technologies and integration become cheaper. 60 GHz band is especially attractive since around 7 GHz unlicensed bandwidth is allocated internationally for ultra wide band communications. For detailed information about regulations and standardizations of 60 GHz band, please refer to IEEE 802.16, IEEE 802.15 standards. As the frequency increases, additional constraints on the electrical properties of the dielectric materials arise. Many materials considered as low loss at microwave frequencies, have unacceptably higher losses at around 60 GHz. Factors such as substrate water absorption which are not critical at lower frequencies might cause more trouble at millimeter wave [1]. Costumers are after not only good electrical performance, but also cost effective solutions.

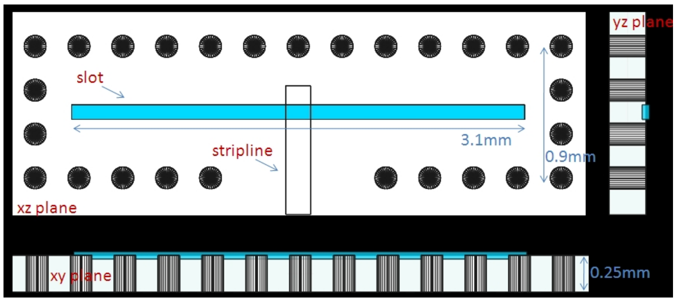
Low temperature co-fired ceramic (LTCC) and liquid crystal polymer (LCP) are the two most frequently preferred technologies at millimeter wave [2], [3]. They both offer good electrical performance however LCP has lower cost [4]. In this paper two cavity backed slot (CBS) antennas designed to operate at 60 GHz are presented. The antennas are chosen to have similar physical properties apart from the dielectric materials used. They are both backed by cavities with pin curtain walls [5]. One cavity is on LTCC substrate whereas the other one is filled with LCP. The antennas are analysed using FDTD method. The performances of these two antennas are judged by their frequency responses, radiation patterns and efficiencies.

II. Antenna Model

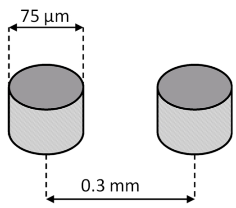
Two antennas are modelled and simulated using an enhanced FDTD method with software developed by Bristol University CEM Group.



(a) CBS on LTCC



(b) CBS on LCP



(c) Pin curtain dimensions

Fig. 1. Dimensions of the CBS antenna

A. *CBS antenna on LTCC*

The slot is backed by a cavity to get a unidirectional radiation of which dimensions can be seen in Figure 1(a). The antenna is fed by a stripline from its mid-plane. The cavity is on a substrate having a dielectric constant of 5.4 and loss tangent of 0.0015 representing LTCC [3]. The thickness of the substrate is chosen to be 200 μm. One reason is that the thickness of the substrate for the stripline should be less than $\frac{\lambda_g}{4}$ which is 5.38×10^{-4} in our case, in order to suppress TE and TM modes. Furthermore two layers are needed for the stripline to be printed on inner layer for this model. Note that the layer thickness of LTCC in the market ranges from 80 to 125 μm. Pin curtains are inserted to form the side walls of the cavity as proposed in [6], [7]. Stripline length is optimized to get the best return loss. The slot is considered to be thin and the lowest slot resonance is defined by its length. The cavity mode with the lowest resonant frequency is TE_{101}, and it is calculated to be at $\sim$ 109 GHz by Equation 1. That is why the operating frequency of this antenna is primarily affected by the size of the slot although the cavity dimensions do have a small effect on the frequency response.

$$f_{nml} = \frac{c}{\sqrt{\epsilon_r}} \sqrt{(\frac{l}{2d})^2 + (\frac{l}{2d})^2 + (\frac{l}{2d})^2} \qquad (1)$$

B. CBS antenna on LCP

Another CBS antenna with similar physical properties is modelled on LCP. The electrical properties of ULTRALAM 3850 is used in the model which are $\epsilon_r = 2.9$ $tan\delta = 0.0049$ [1], [8]. The dimensions of the antenna are given in Figure 1(b). Substrate thickness is chosen as 250 μm.

C. Pin Curtains

The use of the pin curtains here is expected to improve the manufacturing repeatability and the integration with other SIW structures which are becoming common for various reasons such as light weight, low cost, and compact size [9]. The dimensions of the pins which are labelled in Figure 1(c) are not critical in terms of antenna performance, since the cavity mode is not used for the application. However the leakage from the pin curtains should be kept low while following the design restrictions due to the manufacturing capabilities. There are still some restrictions in terms of via diameter and pitch, and line or slot width since the sizes get smaller at 60 GHz. An example of design rules for LTCC provided by Murata Manufacturing Co. is the following: $Line/Slot\,width = 100\mu m\, on\, surface\, layer,\, 75\mu m\, on\, inner\, layer,\, via\, diameter = 100\mu m\, and\, via\, pitch = 300\mu m.$

III. Simulations and Results

The antennas are designed and optimized using FDTD simulations. Conductors are taken as perfect and the conductor loss is calculated separately using perturbation [10]. Dielectric loss is still taken into consideration although both materials have very low loss tangents.

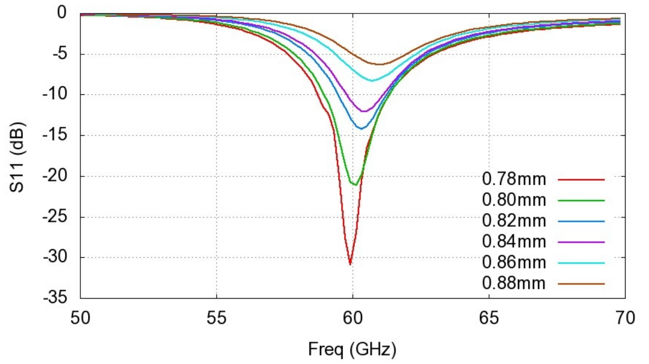


Fig. 2. Tuning of CBS antenna on LCP, feed line length changes from 0.78 to 0.88 mm

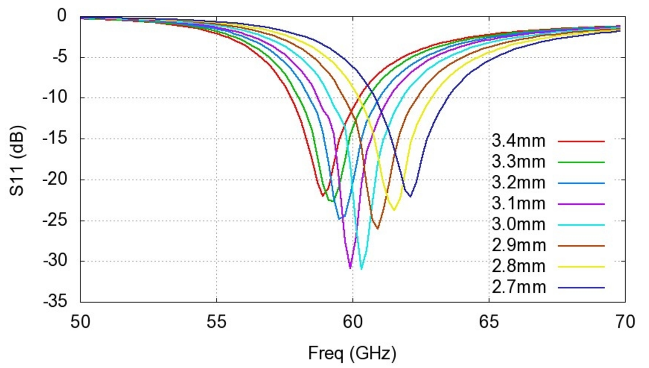


Fig. 3. Tuning of CBS antenna on LCP, slot 3.4 to 2.7 mm

A. Return Loss and Radiation Pattern

The feed line lengths are optimized to have the best return loss for both antennas. The tuning of S11 is shown in Figure 2 while feed line length of CBS atenna on LCP is varied from 780μm to 880μm. the The slot lengths are optimized to set the operating frequencies to 60GHz. Figure 3 shows the response of the LCP antenna to different slot lengths. Finally 22 and 31 dB return losses are observed at 60 GHz for LTCC and LCP respectively. The comparison of the

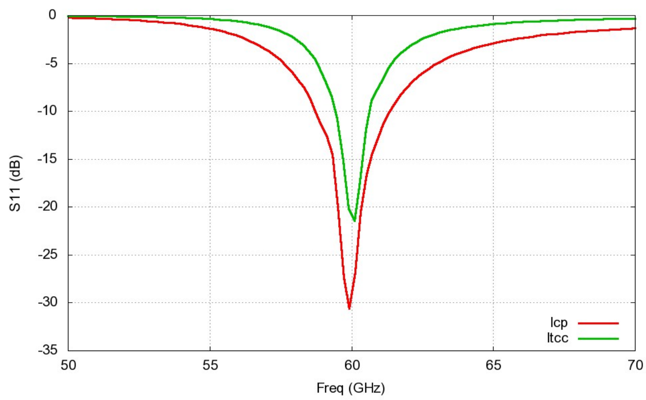
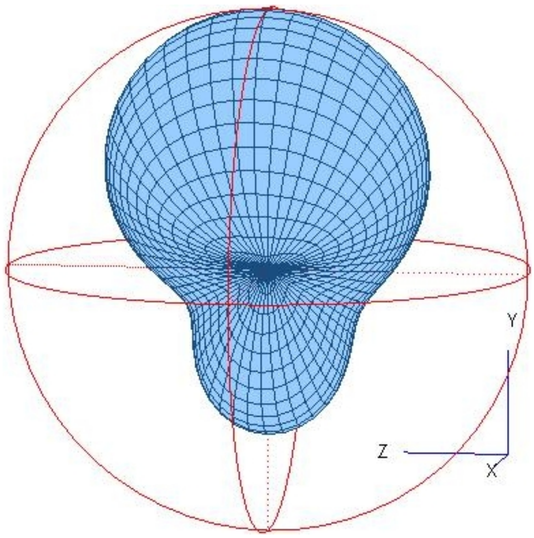
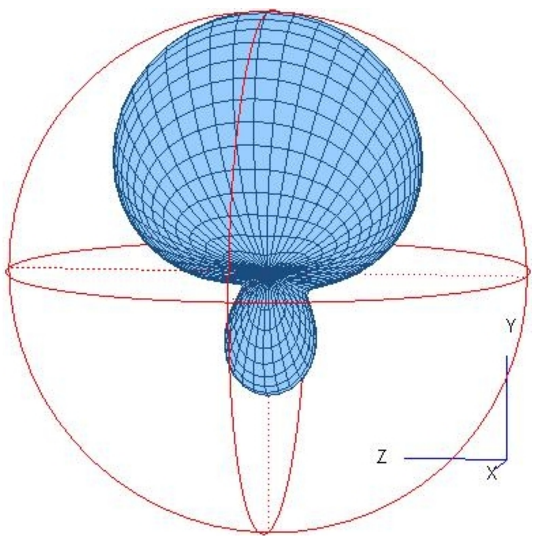


Fig. 4. Frequency response of the CBS antennas

frequency responses of the antennas can be seen in Figure 4. Figure 5 shows the 3D radiation patterns of each antenna at 60 GHz where the level at the centre of the plot is -10dB relative to that at the outside. The patterns are similar to each other as expected while LTCC shows more back radiation. Main lobes are directed at an angle of $\theta = 90^0, \phi = 90^0$ for both antennas. The radiation patterns are processed to get the directivity and polarisation purity and LCP has a better performance in these detailed radiation properties which are given in Table I.



(a) CBS on LTCC



(b) CBS on LCP

Fig. 5. 3D Radiation Patterns of the CBS antennas

B. Efficiency Calculations

In order to calculate the efficiency, dielectric loss and conductor loss figures are needed.

TABLE I
RADIATION CHARACTERISTICS OF THE CBS ANTENNAS

	CBS on LTCC	CBS on LCP
Directivity	5.7dB	6.4dB
Cross Pol Level	17%	14%

1) Dielectric Loss: Dielectric loss is calculated using the total radiated power of each antenna with and without introducing loss to the dielectric material. Loss tangents are taken to be 0.0015 and 0.0049 for LTCC and LCP respectively as mentioned in 'Antenna Model'. The ratios of total radiated powers in lossy to lossless cases for LTCC and LCP are 0.977 and 0.948 respectively. This is an expected result as the loss tangent of LCP is higher than LTCC.

2) Conductor Loss: The conductor loss is calculated by perturbation. First surface current J_s is reached using Equation 2, then it is worked with the surface resistivity of the copper at 60 GHz to find out the loss.

$$\overline{J_s} = \widehat{n} \times \overline{H} = \overline{H_t} \tag{2}$$

There are three components to be calculated: loss on the solid walls of the cavity, pin curtain walls of the cavity and the feed line. For the solid walls and the feed line, the field distribution is stored on and one FDTD cell below the plane of the conductor sheet by frequency snapshots taken at 60 GHz. The snapshots can be seen in Figure 6. Since the H field is continuous in the non-existence of the metal sheet, J_s on a conductor surface can simply be reached by subtracting H_t values on the snapshots, element by element for each cell in the model. Conductivity of copper is taken as $5.813 \times 10^7 Sm^{-1}$, and the surface resistivity is calculated to be 0.064 at 60 GHz using Equation 3 where ω is the angular frequency, μ is the absolute magnetic permeability and σ is the conductivity [11]. The equation to calculate the loss is given in 4 and the values normalized to the total radiated power are given on Table II. Real part of the tangential components of $\overline{H}$ field on xz-plane at feed-line level are plotted in Figure 7. Figure 7(a) and (b) show the distribution in CBS antenna on LTCC and Figure 7(c) and (d) in CBS antenna on LCP.

$$R_s = \sqrt{\frac{w.\mu}{2.\sigma}} \tag{3}$$

$$Loss\, on\, conductor\, sheets = |\overline{J_s}|^2 \times R_s \times unitarea \tag{4}$$

Conductor loss on the pin curtains is calculated with a similar approach using only one frequency snapshot taken on the mid-plane of the pins. This time, H_z values when the

TABLE II
CONDUCTOR LOSSES NORMALIZED TO THE POWER RADIATED IN LOSSLESS CASE

	CBS on LTCC	CBS on LCP
Feed Line	0.042	0.009
X Wall	0.093	0.019
Y Wall	0.085	0.023
Z Wall	0.051	0.016
Pin Curtains	0.012	0.003

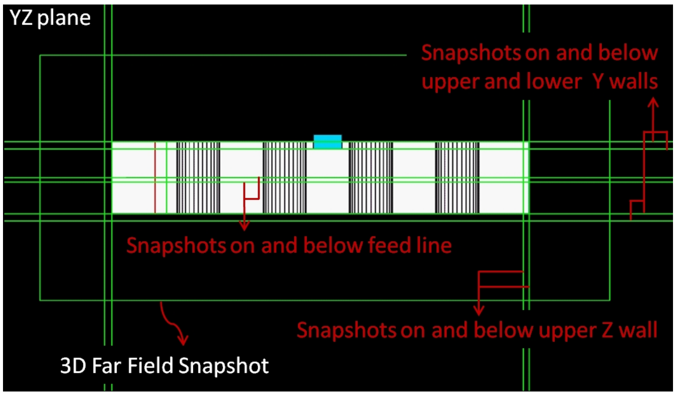


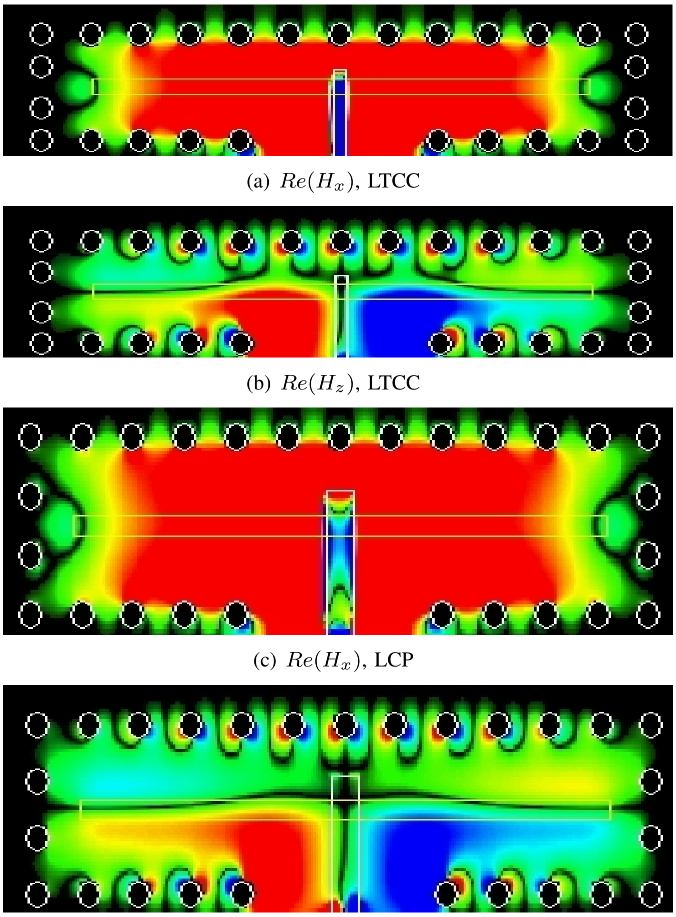
Fig. 6. Frequency snapshots taken to calculate the fields on conductor sheets

field is tangential to the pins along x-axis, and H_z values one x-cell below are subtracted from each other to find J_y as seen in Equation 5. Distribution of the real part of H_z in the mid-plane of a pin and the observation points are given in Figure 8. These currents flow from the outer surface of the pins with a skin depth of $2.695 \times 10^{-7}m$. The J_y values along the upper z pin curtain of the cavity of CBS antenna on LCP is given in Figure 9. The pins stay at positions x = 123, 147, 171, 195, 221, 247, 271, 295, 319 and 7 of them are in the range of the graph. One can notice them easily since the current goes down to zero towards the centre of the pin. Equation 6 is used to calculate the loss on the pins while assuming that the surface current does not change along the pin axis. The heights of the pins are 0.2 mm and 0.25 mm for LTCC and LCP respectively.

$$J_y = |\overline{H_{z1}} - \overline{H_{z2}}| \tag{5}$$

$$Loss\,on\,pins = (2\pi.r_2.J_y)^2 \times R_s \frac{L}{\pi(2.r_1 - \delta_s)} \tag{6}$$

3) Efficiency: The final efficiency values calculated by equation 7 are 62% and 87% for LTCC and LCP respectively. Note that, η_m is the mismatch efficiency and η_Ω stands for the conductor and dielectric losses. Mismatch efficiencies are 0.92 and 0.94 for the two models and it is calculated by the formula $1 - \Gamma^2$.



(a) $Re(H_x)$, LTCC

(b) $Re(H_z)$, LTCC

(c) $Re(H_x)$, LCP

(d) $Re(H_z)$, LCP

Fig. 7. Tangential components of H field on mid-plane of the antennas (feed line level)

$$Efficiency = \eta_m.\eta_\Omega. \tag{7}$$

IV. CONCLUSIONS

Two 60 GHz slot antennas are designed which are backed by cavities on LCP and LTCC. The performance of the antennas are compared to demonstrate the effect of the dielectric material by keeping the other factors as constant as possible. It is shown that LCP offers better performance in terms of efficiency and radiation purity as well as having lower cost.

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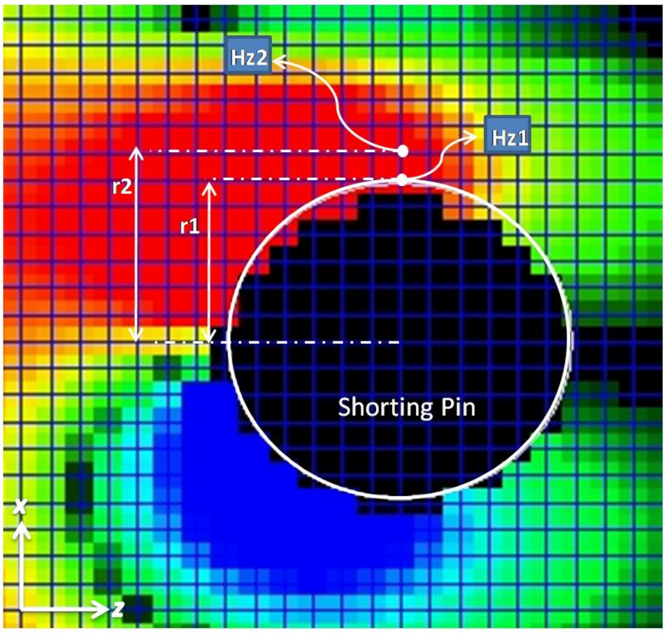

Fig. 8. Top view of the pin with FDTD mesh and Real Hz distribution

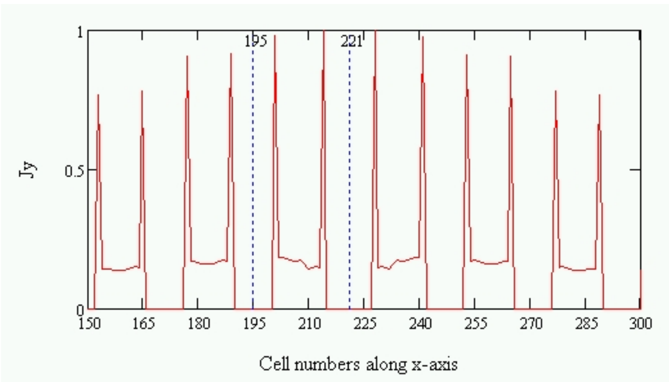

Fig. 9. Jy along the upper z pin curtain of the CBS antenna on LCP, markers show the central position of some pins

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